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13. ABSTRACT (Maximum 200 words)

Consistent with our tasks, we have further improved our micro-size light emitter output efficiencies by optimizing device layer structures, including superlattice structures for enhancing the hole concentration, the thickness of the top Mg doped p-type layer to reduce the light absorption, and the structure of the active region. We have also carried out measurements on the size dependence of the micro-size light emitter characteristics. It was found that the micro-LEDs were very efficient and the heating effect was not significant in micro-LEDs that are greater than 10 μm. Our results also revealed that the operating speed increases with decreasing micro-LED size and the response time reduced from 0.21 ns for 15-μm LEDs to 0.15 ns for 8-μm LEDs. Several integrated photonics devices have been fabricated and their operation under current injection has been achieved. Sub-micron waveguides have also been fabricated from AlGaN/GaN multiple quantum wells and their optical properties have been measured. Effects related to reduced size have been observed. The ability of 2D array integration with advantages of high speed, high resolution, low-temperature sensitivity, and applicability under versatile conditions, make III-nitride micro-LEDs a potential candidate for light sources in short-distance optical communications.

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The main objectives of this Phase I research are to

- Further develop III-nitride microcavity photonic device technologies;
- Demonstrate the feasibility of achieving electrically pumped III-nitride microcavity lasers;
- Assess the feasibility of integrating miniaturized light emitter arrays with waveguides.

The objectives are to be accomplished through the work plan that can be divided into five tasks, which are summarized in Table I.

Table I. Proposed Task Schedule Based on the Month After Receipt of Phase I Award

Tasks	Time, Months								
	Phase I Duration						Optional Duration		
	1	2	3	4	5	6	7	8	9
1. Optimizing μ-cavity emitter materials & structures									
• Blue μ-cavity photonic materials & device structures		□	□	□	□	□	□		
• UV μ-cavity photonic materials & device structures						□	□	□	
2. Optimizing μ-cavity emitter fabrication processes									
• Patterning by lithography and ICP dry etching		□	□	□	□	□	□		
• Self-organization by selective area overgrowth						□	□	□	
3. Characterization of individual μ-light emitters • I-V, L-I, E-L characteristics vs. μ-cavity lateral size; • Polarization and directionality dependence of the lasing spectra: • Turn-on and off speed vs. μ-cavity lateral size; • Operating lifetimes under pulsed and cw injections.	□	□	□	□	□	□	□		
4. Coupling between μ-emitter arrays with waveguides							□	□	□
5. Final Report									□

Consistent with our tasks, we have carried out the following studies:

1. Further improving blue microcavity photonics device structures.

We have investigated methods for further enhancing the emission efficiency of InGaN/GaN LEDs. The new LED wafers were grown on sapphire substrates with 30 nm GaN buffer layers by low pressure MOCVD. The device structure includes a 3.5 μm of silicon doped GaN, 10 periods of Si doped superlattice consisting of alternating layers of AlGaN (30 Å)/GaN (30 Å), a 0.05 μm of Si doped GaN, two periods of InGaN (30 Å)/GaN (25 Å) undoped quantum well active region. Followed by 14 periods of Mg doped superlattice consisting of alternating layers of AlGaN (30 Å)/GaN (30 Å), and 0.1 μm Mg-doped GaN epilayer. The structure was then thermally annealed at 950 °C for 8 seconds in nitrogen in a rapid thermal-annealing furnace to activate Mg acceptors. By incorporating the modified superlattice structure into the device and decreasing the top Mg-doped p-type layer thickness to 0.1 μm, we have enhanced the power output of our conventional broad area (300 x 300 μm^2) purple LEDs (408 nm) by a factor of 2. Further improvements in materials and structural qualities are needed in order to fabricate microcavity lasers based on these materials.

2. Characterization of micro-size light emitters

III-Nitride Blue Micro-LEDs

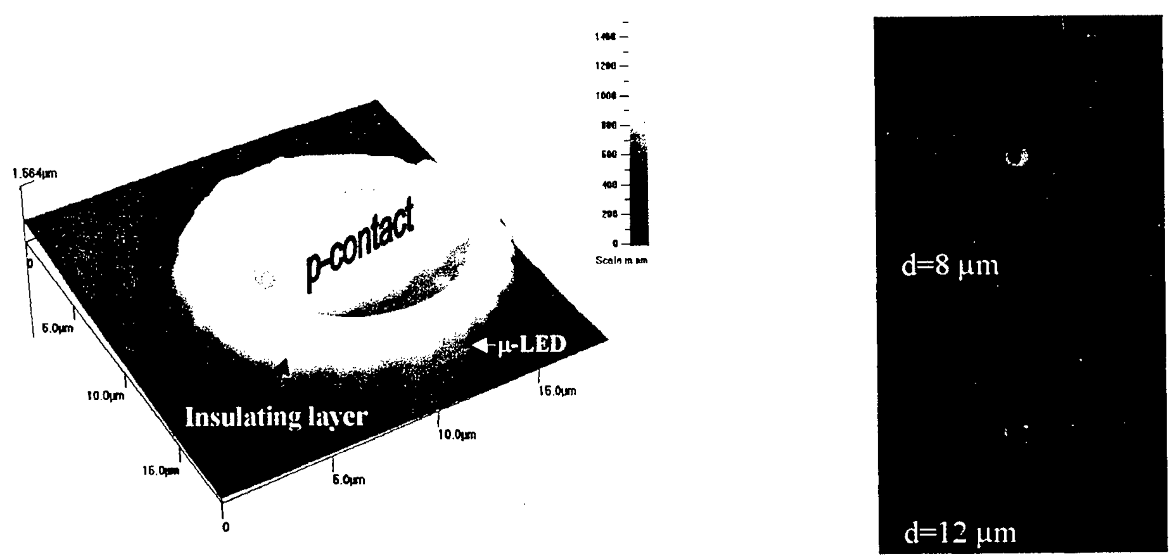

Fig. 1 (a) An AFM image showing a fabricated micro-LED. (b) Optical microscope images of individual μ-disk LEDs in action.

Dring the reporting period, individual μ-disk LEDs of varying diameters from 5 to 20 μm were fabricated by photolithography patterning and inductively coupled plasma (ICP) dry etching. Bilayers of Ni (20nm)/Au (200nm) and Al (300nm)/Ti (20nm) were deposited by electron beam evaporation as p- and n-type Ohmic contacts. The p-type contacts and the n-type contacts were thermally annealed in nitrogen ambient at 650 °C for 5 min. A dielectric layer was deposited by e-beam evaporation after the μ-LEDs formation for the purpose of isolating p-type

contacts from the etch-exposed n-type layer. This allowed us to carry out preliminary measurements on the size dependence of the μ-LED characteristics. Figure 1 (a) shows an atomic force microscope (AFM) image of a fabricated μ-LED. As can be seen from Fig. 1(a), the p-type contact was connected to the top p-layer by opening a hole through the insulating dielectric layer. The size of the p-type contact is about 4 μm in diameter. Figure 1(b) shows optical microscope images, taking from the top (p-type contact side), of two representative InGaN/GaN QW μ-LEDs with diameters d=8 and 12 μm in action with an injected current of 2 mA. The p-type contacts on the top layers are also visible in Fig. 1(b).

The I-V characteristics of μ-disk LEDs of varying sizes and a conventional board-area LED (300 x 300 μm^2) fabricated from the same wafer are plotted in Fig. 2 (a) linear and (b) semi-logarithmic scales. It is clearly seen that the turn-on voltages for individual μ-LEDs are larger than that of the broad-area LED. Among the μ-LEDs of different sizes, the turn-on voltage increases with decreasing μ-LED size. The slope of the Log I vs. V plot in Fig. 2(b) reflects the ideality factor, n (=1/slope). It is clear that the ideality factor of μ-LEDs (n=18.5) is larger than that of the broad-area LED (n=6.4). There is only a weak size dependence of ideality factor for the μ-disk LEDs. The larger ideality factor reflects the enhanced non-radiative recombination in μ-LEDs, which is most likely a result of enhanced surface recombination around the edge of the disk of μ-LEDs.

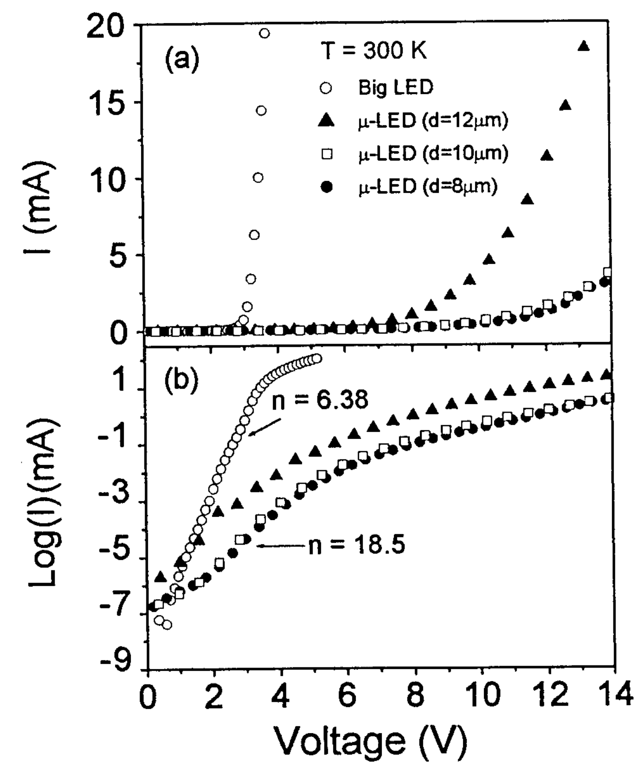

Figure 2 I-V characteristics of μ-LEDs of varying sizes (d =8, 10, and 12 μm) and a broad-area LED (300 x 300 μm^2) in (a) linear and (b) semi-logarithmic plots.

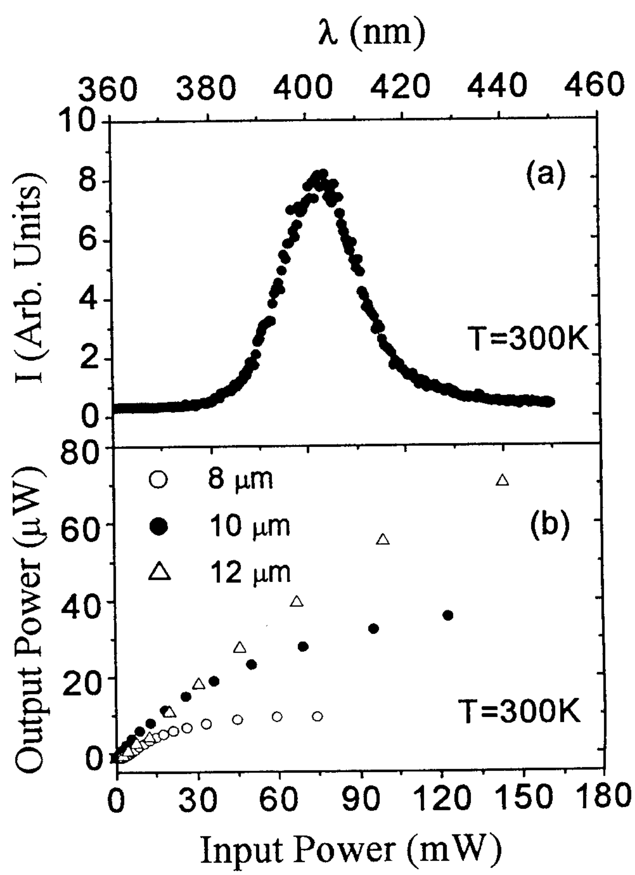

Figure 3 (a) E-L emission spectrum of a purple μ-LED. (b) Output power vs. input power (L-I) plot of μ-LEDs of different sizes.

Figure 3 shows a room temperature electro-luminescence (EL) spectrum of a purple μ-LED measured at a forward current of 2 mA. Fig. 3(b) plots the output power vs. input power measured from the sapphire substrate side for three unpackaged μ-LEDs of different sizes. Heating effects become more prominent as the size of μ-LEDs decreases. For μ-LEDs with d=12 μm, the output power increases almost linearly with input power in the entire measured range. However, for μ-LEDs with d=8 μm, the output power saturates at about 10 μW for input power above about 45 mW. As expected, heat dissipation is more difficult in μ-LEDs with reduced sizes, which causes power output saturation. However, we believe that appropriate packaging processes can improve the performance.

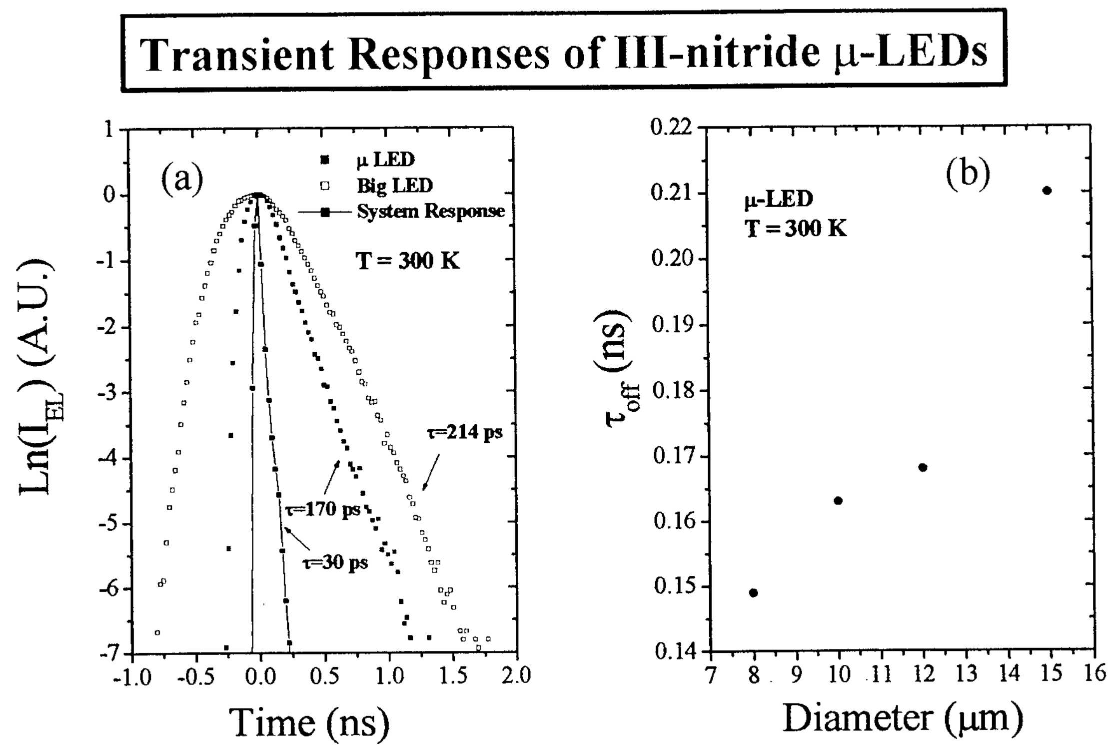

Fig. 4 (a) Transient responses of a microdisk LED of 12 μm in diameter and a broad-area LED (300 x 300 mm^2) in response to picosecond electrical pulses. The turn on time of the microdisk LEDs is on the order the system response (< 35 ps). (b) The size dependence of the turn-off time of the microdisk LEDs. τ_{off} decreases with a decrease of μ-LED size. It reduced from 0.21 ns for d=15 um to 0.15 ns for d=8 um.

These μ-LEDs have potential applications in short distance optical communications. For these applications, the speed is one of the most crucial parameters, which has been measured by time-resolved EL. In Fig. 4 we plotted (a) transient responses of a μ-LED and a conventional broad-area LED and (b) the size dependence of the "turn-off" time, τ_{off}, of μ-LEDs. The turn-on response was very fast and could not be measured. However, the turn-off transient was in a form of single exponential and its lifetime, τ_{off}, could be determined. It was found that τ_{off} decreases with a decrease of μ-LED size. It reduced from 0.21 ns for d=15 μm to 0.15 ns for d=8 μm. This behavior is also expected since the effects of surface recombination are enhanced in smaller μ-LEDs. On the other hand, the increased operating speed may also be a result of an enhanced radiative recombination rate in μ-LEDs. With this fast speed and other advantages such as long

operation lifetime, III-nitride μ-LED arrays may be used to replace lasers as inexpensive short distance optical links such as between computer boards with a frequency up to 10 GHz.

3. Fabricating novel μ-light emitter structures and studying the coupling between μ-structures

We have succeeded in fabricating double-ring μ-cavity light emitters. As illustrated in Fig. 5, their operation under current injection has been achieved. We have obtained a bonding scheme (as shown in Fig. 6), that will allow the detailed characterization of these novel light emitters under different current injection conditions.

III-Nitride Double-Ring μ-Cavity Light Emitters

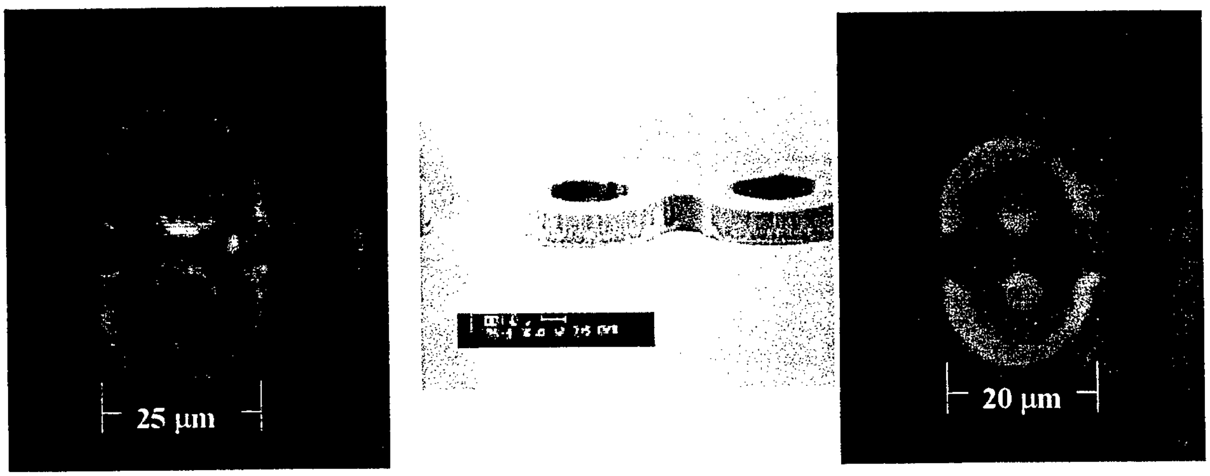

Fig. 5 Optical microscope images of III-nitride double-ring microcavity emitters under operation. Center: Scanning electron microscopy (SEM) image of a double-ring microcavity emitter prior to electrical contacts fabrication.

III-Nitride Double-Ring μ-Cavity Light Emitters

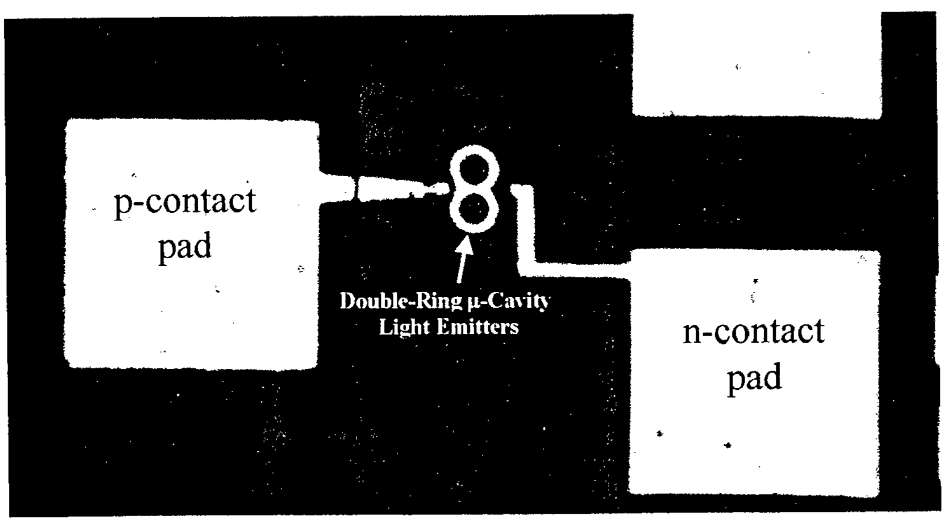

Fig. 6 Optical microscope image of a fabricated III-nitride double-ring microcavity emitter with n- and p-contact pads, which can be used for current injection and charaterization.

We have also successfully fabricated submicron waveguide structures based on AlGaN/GaN multiple-quantum wells (MQW). The waveguides are important component in integrated photonics circuits. The waveguides were patterned with widths varying from 0.5 – 2.0 μm and orientations varying from -30° to 60° relative to the a-axis of GaN. Fig. 7 (top) shows the SEM images of two sets of waveguides. We found that when the width of waveguides was reduced to below 0.7 μm, as illustrated in Fig. 7 (bottom), the emission peak position and line-width of the localized exciton emission were found to vary systematically with orientations of the waveguides and followed the six-fold symmetry of wurtzite structure. This is related to the anisotropy of the exciton/carrier diffusion coefficient along the different crystal orientations in quasi one-dimensional case.

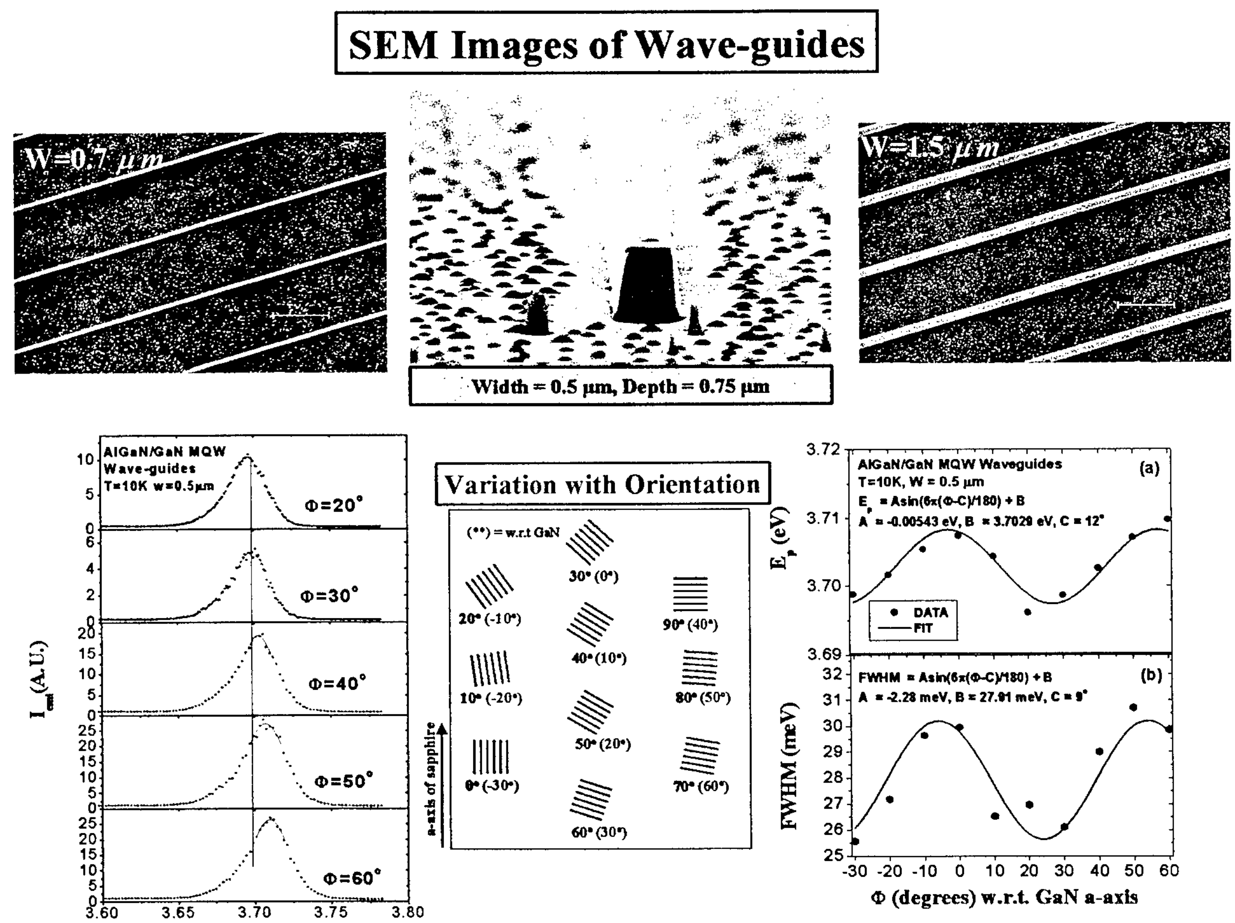

Fig. 7 (Top) SEM images of AlGaN/GaN MQW waveguides. (Bottom: left) Low temperature (10 K) cw PL spectra from AlGaN/GaN MQW waveguides of different line orientations; (Bottom: right) the variation of (a) the spectral peak positions (E_p) and (b) full width at half maximum (FWHM) of the PL emission line at 10 K. The solid line is the sinusoidal fit of the data with 6-fold symmetry of hexagonal structure. (Center) Schematic of a set of AlGaN/GaN QW waveguides with varying orientation.

By analyzing the arrangements of Ga^{3+} and N^{3-} ions in a hexagonal GaN crystal, it was clear that the crystal arrangements along the directions parallel to 0°/60° and -30°/30° are different. The a-axis of GaN is shifted 30° with respect to the a-axis of sapphire. Waveguides prepared along -30°/30° (where E_p and FWHM are minimum) and 0°/60° (where E_p and FWHM are maximum) have the following differences in crystal arrangements:

1. The number of ions per unit length in the -30°/30° line is greater than that along the 0°/60° line by a factor of 10:9.
2. The lateral termination of the waveguides for the -30°/30° line is composed of both Ga and N ions while that of the 0°/60° line is either Ga or N.
3. The width covered by 4 columns of ions is larger in the -30°/30° direction than in the 0°/60° direction.

These differences could be the source of the anisotropy of the exciton/carrier diffusion coefficient in the quasi-1D waveguide structures. At 0°/60° orientations, there is slow carrier or exciton diffusion leading to band-filling effect with the result that E_p and FWHM are both maximum. Faster diffusion occurs along the -30°/30° resulting in E_p and FWHM both being minimum. Our results indicate that there is a difference in optical property of submicron structures, shown by the periodic variation in the peak energy E_p and FWHM of the spectra from MQW waveguides at different crystal orientations. This difference is more pronounced in smaller structures.

Our results imply that in photonic structures of submicron sizes are involved, there will be differences in exciton or carrier dynamics. The differences arising from the choice of orientation will result in significant effects in the associated devices. Such devices include optical waveguides, photodetectors and ridge-guide laser diodes. Therefore in the design of these devices, proper attention must be paid in the choice of the orientation of the associated submicron structures.

Integrated μ-structures, such as emitter-emitter and emitter-waveguide will also be fabricated and studied.